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Research complted under this grant has led to the discovery of two mental frames for representing space. One is the spatial framework, based on the egocentric body axes, and the other is intrinsic computation, based on analysis of body sides from an external perspective. Experiments demonstrated that spatial frameworks are used in discourse comprehension and memory for physical scenes. Intrinsic computation was observed in perception of model scenes. The current research extends this program by exploring the conditions under which people use spatial frameworks versus intrinsic computation. Experiments determined whether diagrams and models induce or favor different mental representations. Diagrams were studied because they are representational but also have their own spatial properties. A second question was whether the spatial framework and intrinsic computation analyses different processes for expressing spatial knowledge in memory versus perception. Previous research observed spatila frameworks in memory, suggesting that it is a general representation for spatial memory. In contrast, intrinsic computation has been observed in perception of observed scenes. Results of the current research indicate that people employ spatial frameworks for memory of 3D models and intrinsic computation for both memory and perception of

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diagrams. Instructions to use a given frame alters people's performance. The kind of depiction and task favors a particular frame, but the use of mental frames is under strategic control. A second series of experiments explored how physical asymmetry of body axes produces differential accessibility, and whether functional laterality plays a role in determining the accessibility of left/right locations relative to other directions. It was found that differences in accessibility are not produced by a decision process for distinguishing directional poles of spatial axes. Rather, accessibility depends on the salience of the entire body axis. Laterality and handedness do not affect the accessibility of objects associated with the left/right axis. A third project examined rehearsal of spatial location in visual perception. Spatial location is effortfully rehearsed, rather than encoded automatically. The rehearsal process depends critically on eye movements between locations. Sequentially presented locations are stored primarily by their temporal order of presentation.

~~**Progress report**~~
Final Report.

*title:*

Spatial Frameworks for Perceived Environments

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## Objectives

Research completed under this grant has led to the discovery of two mental frames for representing space. One is the spatial framework, based on the egocentric body axes, and the other is intrinsic computation, based on analysis of body sides from an external perspective. Experiments demonstrated that spatial frameworks are used in discourse comprehension and memory for physical scenes. Intrinsic computation was observed in perception of model scenes. The current research extends this program by exploring the conditions under which people use spatial frameworks versus intrinsic computation. Experiments determined whether diagrams and models induce or favor different mental representations. Diagrams were studied because they are representational but also have their own spatial properties. A second question was whether the spatial framework and intrinsic computation analyses reflect different processes for expressing spatial knowledge in memory versus perception. Previous research observed spatial frameworks in memory, suggesting that it is a general representation for spatial memory. In contrast, intrinsic computation has been observed in perception of observed scenes. Results of the current research indicate that people employ spatial frameworks for memory of 3D models and intrinsic computation for both memory and perception of diagrams. Instructions to use a given frame alters people's performance. The kind of depiction and task favors a particular frame, but the use of mental frames is under strategic control.

A second series of experiments explored how physical asymmetry of body axes produces differential accessibility, and whether functional laterality plays a role in determining the accessibility of left/right locations relative to other directions. It was found that differences in accessibility are not produced by a decision process for distinguishing directional poles of spatial axes. Rather, accessibility depends on the salience of the entire body axis. Laterality and handedness do not affect the accessibility of objects associated with the left/right axis.

A third project examined rehearsal of spatial location in visual perception. Spatial location is effortfully rehearsed, rather than encoded automatically. The rehearsal process depends critically on eye movements between locations. Sequentially presented locations are stored primarily by their temporal order of presentation.

## Status of Effort

The first set of experiments to determine when spatial frameworks and intrinsic computation are used has been completed. The experiments provided clear answers to the motivating questions. The results raise at least two new issues that will frame future research. One concerns the kind of pictorial depth cues that could lead people to spontaneously create spatial frameworks for diagrams. A second set of questions is whether there is a limit to strategic control of frame selection, and whether spatial frameworks and intrinsic computation are better suited for different spatial tasks. Preparation of pilot studies to examine these issues is underway. The second series of experiments is on-going. W. Wright has completed two experiments and will base his M.A. thesis on this work. Experiments to examine left/right discriminability on location accessibility are being designed. Studies of spatial rehearsal have been completed, and I. Subbiah has completed her Ph.D. dissertation on this work.

## Accomplishments/New Findings

*Memory and Perception of a Simple Spatial Situation*

The current research has focussed on the prototypic spatial situation of a person surrounded by objects. Subjects learned scenes containing a person surrounded by objects to his/her six body sides (front, back, head, feet, left, and right). The same basic task was employed in all experiments. Subjects first studied a scene presented in a diagram or a 3D model. The person in the scene then rotated to face another object and/or changed posture (e.g., from upright to reclining). Subjects were presented with direction probes - terms referring to the person's six body sides - and they named the object currently at that direction relative to the person. Probes were answered either from memory or while viewing the scene. Because certain body axes have a favored status in our interactions with the world, they are more salient to thinking about spatial relations. These differences lead to differences in retrieval times for spatial relations and indicate the spatial concepts organizing memory or perception.

*Spatial Framework Analysis.* According to this analysis, subjects construct a mental spatial framework consisting of extensions of the three body axes, head/feet, front/back, and left/right, and associate objects to that framework. The accessibility of an axis depends on characteristics of the body and the perceptual world. For an upright observer, the head/feet axis is most accessible because it is physically asymmetric and correlated with the fixed environmental axis of gravity. The front/back axis is next most accessible. It is not associated with a fixed environmental axis but is strongly asymmetric, separating the world that can be seen and manipulated from the world that cannot be easily perceived or manipulated. The left/right axis is least accessible because it has no salient asymmetries. For the upright observer, the spatial framework analysis predicts that people should be fastest to identify objects at the head or feet, followed by front or back, followed by left or right. In addition, because perceptual and behavioral asymmetries so strongly favor front over back, people should be faster to front than back.

The situation changes for a reclining person. The head/feet axis is no longer correlated with gravity, so the accessibility of axes depends solely on their asymmetries. The perceptual and behavioral asymmetries of the front/back axis are stronger than those of the head/feet axis. The left/right axis has the weakest asymmetries. Thus, for a reclining person, identification along front/back should be faster than head/feet, which should be faster than left/right.

*Intrinsic Computation Analysis.* According to this analysis, observers identify the intrinsic sides of the person by using the general perceptual mechanisms used in object recognition, which involves extracting the axes of objects. Some intrinsic axes of objects are more readily determined than others. Research has demonstrated that the top/bottom axis (the head/feet in humans) is primary in object perception and the first axis abstracted during object recognition. People are faster to identify the top/bottom (head/feet) than the front/back and the left/right of objects at all orientations (including reclining). The left/right axis is derived from knowing the top or bottom

and front or back sides of an object and is necessarily slowest. On this basis, the main prediction of the intrinsic computation analysis is that an observer will *always* be fastest to identify objects at the head/feet, then the front/back, and finally the left/right of a viewed person, regardless of the person's posture. Thus, the main way to distinguish the use of spatial frameworks from intrinsic computation is to compare patterns of response times for head/feet and front/back across upright and reclining orientations.

*Empirical Research.*

One issue addressed by our research was whether diagrams and models of scenes induce different mental representations. Previous experiments in this project have found that people create spatial frameworks for memory of models, but use intrinsic computation during perception. At issue is whether these findings reflect anything specific to 3D models versus 2D diagrams. A second question was whether the spatial framework and intrinsic computation analyses reflect different processes for expressing spatial knowledge in memory versus perception.

*Model scenes.* In one experiment, subjects viewed a 3D model of a scene containing a person surrounded by drawings of objects at the person's six sides. Subjects responded to direction probes from memory or during observation of the model. When subjects responded from memory, response times conformed to the spatial framework pattern. Critically, front/back was faster than head/feet for reclining dolls. This suggests that subjects mentally adopt the person's perspective and construct a mental spatial framework. When subjects responded while viewing the scene, subjects were faster to head/feet, followed by front/back, followed by left/right for *both* upright and reclining postures. This indicates that subjects used intrinsic computation. A second experiment replicated and extended the the previous experiment, including an upside down orientation. Subjects exhibited the spatial framework pattern and were overall slower overall when the person was not upright. Response times were faster to head/feet than front/back when the person was upsidedown. The results of the two experiments indicate that people mentally adopt the perspective of the person they have viewed in the scene and impute the egocentric properties of their own perspective onto that person.

*Diagrammed Scenes.* An experiment distinguished between the spatial framework and intrinsic computation analyses for diagrammed scenes. Subjects viewed a series of diagrams of scenes. The orientation of the figure was varied within-subject so that the person was upright, reclining to the left, reclining to the right, and upsidedown on an equal number of trials. Subjects received a direction probe for each diagram and named the target at that direction. At all orientations, subjects were faster to head/feet than front/back than left/right. Thus subjects employed intrinsic computation in perception of diagrams. Even though the drawings were highly representational, they tapped the same perceptual spatial concepts that guide the locating of objects in observed 3D model scenes.

An experiment examined memory for scenes depicted in diagrams. Subjects studied

diagrams of scenes, learning the positions of objects around a person. Subjects then responded to direction probes from memory. Response times to direction probes conformed to predictions of the intrinsic computation analysis; i.e., they were faster to head/feet than front/back at *all* orientations of the person. This contrasts with the finding that subjects create spatial frameworks for memory of models.

*Strategic Effects.* People responded differently in memory for models and diagrams, which reflects the use of two different mental frames of reference, spatial frameworks versus intrinsic computation. The use of one or the other frame probably does not depend on the kind of depiction itself, but on the ease with which three-dimensional information can be extracted from the depiction, and how the viewer interprets it. If so, people should be able to alter how they represent scenes in our paradigm. A viewer should be able to form a spatial framework of a diagram and use intrinsic computation for a model. Two experiments tested this possibility. In both, subjects were given special instructions concerning the perspective to adopt on scenes. The goal was to determine whether the kind of mental representation created in memory is under strategic control.

In the first experiment, subjects viewed diagrams that referred to themselves in a scene and were explicitly told to create a mental model of themselves in the scene. Subjects responded to direction probes from memory. Response times conformed to the predictions of the spatial framework analysis. Critically, subjects were faster to head/feet than front/back for the upright and upsidedown orientations, but faster to front/back than head/feet for the reclining orientations. In the second experiment, subjects viewed 3D model scenes. Subjects were instructed to mentally represent the model from an external perspective by forming a visual image of what the model looked like from their vantage point. Subjects' response times conformed to the intrinsic computation pattern. At all orientations, subjects were faster to head/feet than front/back.

Instructions to adopt the internal perspective on diagrams led subjects to employ spatial frameworks in memory of diagrams. Likewise, instructions to represent diagrams in an external perspective led subjects to use intrinsic computation in memory of models. Thus, both analyses can apply to memory of modelled and diagrammed scenes. The use of one or the other is a strategic factor, depending on how the viewer mentally treats the depiction of the spatial array.

### *Structure of Dimensions and Asymmetry*

Our research has also examined how asymmetry of body axes affects memory for space. We tested between one hypothesis that people identify locations of objects by first accessing the appropriate spatial axis, then performing a decision process to distinguish the two poles of the axis (e.g., front from back) and another hypothesis that asymmetries make certain axes more salient as a whole because the axes are better for categorizing space. The question addressed was whether the spatial framework pattern of response times results from the salience of body axes at which objects are located, or from difficulty or confusion during a "pole decision" during which the subject distinguishes individual directions.

Subjects read narratives that described the prototypic situation. After reading the first part of

the narrative, subjects turned to a computer and were tested. The name of an object appeared on the screen and subjects indicated its location. Two kinds of responses were collected. For half the narratives, subjects responded to probes by naming the specific direction at which the object was located. For the other half, they will responded by naming the body axis (left/right, front/back, or head/feet) along which the object was located. Responding with the axis of an object relieves the subject of the need to distinguish between the directional poles of that axis. Subjects in the direction decision task exhibited the spatial framework pattern, being faster to head/feet than front/back than left/right for the upright posture, and faster to front/back than head/feet than left/right for the reclining posture. The overall response times and patterns of response times were the same for the axis task. Consequently, it appears that the spatial framework pattern arises because of the differential salience of entire axes, not because of a direction decision stage in processing.

In our second experiment, we investigated the possibility of individual differences in salience of the left/right axis. The difficulty in accessing left and right is related to that axis' lack of physical asymmetries. Nevertheless, this axis does possess *functional* asymmetry to some degree. For the left/right axis, the most common lateralization includes preference for the left or right hand, foot, eye, and ear in performing tasks. The functional laterality of an individual falls between extremes of strong preference for the left or right and little preference for either side. The first case represents strong lateral individuals and the latter alateral individuals. The question addressed by the second experiment was whether strong lateralized people have more salient left/right concepts that lead to faster access of those directions relative to front/back and head/feet.

We screened participants for their functional laterality using standardized tests of laterality, grouping subjects into strongly lateralized and alateral groups. Subjects read narratives like those in the first experiment and were similarly probed for the locations of objects. Only the direction task was used in this experiment. The alateral group was somewhat faster overall than the highly lateral group. The spatial framework pattern was evident in both groups, with subjects being faster to head/feet than front/back than left/right for the upright posture, but faster to front/back than head/feet than left/right for the reclining posture. Most importantly, the degree of functional laterality did not affect the *size* of the difference between response times to left/right and the other two dimensions. These results indicate that functional asymmetry, such as handedness, does not convey greater salience to the left/right axis. The salience of body sides is determined by universal physical and perceptual asymmetries, such as the structural difference between one's head and feet and the orientation of sensory and perceptual mechanisms frontward.

*Memory for Sequences of Spatial Locations*

In research comprising Ilavenil Subbiah's doctoral thesis, we investigated whether spatial locations are stored in memory automatically or effortfully. A well-documented effect in memory for sequences of items is the primacy effect. This is the elevated recall of the first few items

presented in a sequence, resulting from additional rehearsal of these items. In our experiments, subjects viewed an array of forty boxes (locations) on a computer screen. Ten of the boxes were marked by a target in a sequential fashion. Memory for locations of the targets was tested after a delay of one minute.

Three experiments determined that a primacy effect occurs in memory for location when subjects do not engage in concurrent tasks that require eye-movements away from the display during study. Shifting gaze disrupts rehearsal of spatial location.

Three additional experiments further investigated the role of eye-movements in spatial encoding. In one experiment, a concurrent task specifically designed to require subjects to move their eyes to the edge of the display between presentations of targets eliminated the primacy effect. Performing a concurrent auditory localization task did not remove the primacy effect, indicating that concurrent processing of abstract spatial information did not interfere with rehearsal of visually presented spatial items. In a third experiment, subjects were prevented from making eye-movements by having them fixate their gaze on the center of the computer display. Subjects had to process location by shifting visual attention without shifting their eyes. The primacy effect was greatly reduced by this manipulation. These findings show that physical eye-movements between locations are a critical mechanism in encoding visual location.

Two experiments determined whether spatial locations were stored as chains of locations linked by eye-movements, or as clusters of locations organized by spatial proximity. One experiment forced a break in the hypothesized chaining process by changing the appearance of the locations in the sequence. A second experiment examined the order of recall of target locations. Both experiments supported the hypothesis that locations were encoded in terms of temporal order.

**Personnel Supported**

Principle Investigator: David J. Bryant

Associated personnel: Margaret Lanca, graduate student
Ilavenil Subbiah, graduate student
William Wright, graduate student

## Publications

Lanca, M., & Bryant, D. J. (1995). Effect of orientation on haptic line length reproduction. *Perceptual and Motor Skills, 80,* 1291-1298.

Bryant, D. J., Lanca, M., & Tversky, B. (1995). Spatial concepts and perception of physical and diagrammed scenes. *Perceptual and Motor Skills, 81,* 531-546.

Bryant, D. J. (in press). Human spatial concepts reflect regularities of the physical world and human body. In P. Olivier & K-P. Gapp (Eds.), Representation and processing of spatial expressions. Mahwah, NJ: Lawrence Erlbaum Associates.

### Submitted Manuscripts

Bryant, D. J., Tversky, B., & Lanca, M., (1995). *Retrieving spatial relations from observation and memory.* Submitted manuscript.

Bryant, D. J. (1996). *Representing space in language and perception.* Submitted manuscript.

Bryant, D. J., & Tversky, B. (1996). *Mental Representations of Spatial Relations from Diagrams and Models.* Submitted manuscript.

## Interactions

### Presentations

Bryant, D. J., & Lanca, M., *The internalization of geometric principles through evolution.* Poster presented at the 25th Annual Symposium of the Jean Piaget Society, Berkeley, CA, June, 1995.

Bryant, D. J., *Human spatial concepts reflect regularities of the physical world and human body.* Paper presented at the 14th International Joint Conference on Artificial Intelligence, Montreal, Canada, August, 1995.

Subbiah, I., & Bryant, D. J., *Rehearsal and the primacy effect in memory for spatial location.* Poster presented at the 37th Annual Meeting of the Psychonomic Society, Los Angeles, CA, November, 1995.

Bryant, D. J., & Tversky, B., *Acquiring spatial relations from models and diagrams*. Paper presented at the 37th Annual Meeting of the Psychonomic Society, Los Angeles, CA, November, 1995.

Bryant, D. J., *Regularities of the physical world and human body in spatial cognition*. Invited talk. Tufts University, January 22, 1996.

Bryant, D. J., *Mental Frames for conceiving of Space in Diagrams and Models*. Paper presented at the AFOSR Vision, Audition, and Perception Workshop, Wright-Patterson AFB, Dayton, OH, June, 1996.

Wright, W., & Bryant, D. J., *Spatial framework: Differential accessibility of bodily dimensions and effects of lateralization*. Poster presented at the Eighth Annual Convention of the American Psychological Society, San Francisco, CA, June, 1996.

Bryant, D. J., *Mental Frames for Interpreting Direction Terms*. Paper to be presented at the 12th European Conference on Artificial Intelligence (ECAI-96), Budapest, Hungary, 1996.

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